Exhibit A

#8 attach

Draft – 12 Sept. 2000

STRAIN-BALANCED $In_{0.62}Ga_{0.38}As/In_{0.47}Ga_{0.53}As$ (InP) QUANTUM WELL CELL FOR THERMOPHOTOVOLTAICS

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ABSTRACT

For thermophotovoltaic (TPV) applications, there is considerable interest at present in extending the absorption to longer wavelengths for higher overall system efficiencies with lower temperature sources. With strain-balanced $In_{1-x}Ga_xAs/In_{1-y}Ga_yAs$ (InP) Quantum Well Cells (QWCs), where the average lattice-constant of wells and barriers is the same as the InP substrate, the absorption can be extended, while retaining a low dark current. A strain-balanced $In_{0.62}Ga_{0.38}As/In_{0.47}Ga_{0.53}As$ QWC extends the absorption edge beyond that of lattice-matched bulk InGaAs to about 1.8 μm, which is similar to that of GaSb, while the dark current remains at a lower level. We can model the spectral response of InP-based, including strain-balanced, QWCs. Efficiencies for solar (AM1.5G), black-body spectra of 1500–3200 K and selective emitters are presented. Lattice-matched InGaAsP and strain-balanced $In_{0.62}Ga_{0.38}As/In_{0.47}Ga_{0.53}As$ (InP) QWCs show superior performance when compared with bulk InGaAs monolithic interconnected modules and bulk GaSb TPV cells.

INTRODUCTION

Thermophotovoltaics (TPV) is the use of photovoltaic (PV) cells to convert heat radiation, e.g. from the combustion of fossil fuels or biomass, into electricity [1]. The energy spectrum is often reshaped using selective emitters which absorb the heat radiation and re-emit in a narrow band. The re-emitted radiation may be efficiently converted to electric power using a PV cell of appropriate low band-gap.

Higher PV cell efficiencies can be achieved by introducing multi-quantum wells (MQW) into the intrinsic region of a p-i-n diode if the gain in short-circuit current exceeds the loss in open-circuit voltage [2]. A Quantum Well Cell (QWC) in the quaternary system InGaAsP lattice-matched to InP substrates is a promising candidate for TPV applications as the effective band-gap can be tuned, out to ~ 1.65 μm ($In_{0.53}Ga_{0.47}As$), without introducing strain, by varying the well depth and width, to match a given spectrum. The enhancement in output voltage of a QWC is a major advantage for TPV applications [3–5].

There is considerable interest at present in extending the absorption to longer wavelengths for higher overall system efficiencies with lower temperature sources; and lower temperature fossil sources have also lower levels of pollution. Appropriate and inexpensive substrates of the required lattice constant and band-gap are not available, so the lower band-gap material is often strained to the substrate, introducing dislocations which increase non-radiative recombination. In a MQW system, these dislocations can be avoided by strain-balancing the layers; alternating barriers and wells have bigger and smaller lattice-constants, but on average are lattice-matched to the substrate [6]. The aim of strain-balancing techniques is to reduce the average or effective stress to zero by balancing the forces of tensile and compressively strained layers and thereby avoiding the formation of misfit dislocations.

Table 1
Sample description of a strain balanced Quantum Well Cell.

Layer	Thickn. [Å]	Material	Doping
Cap/Contact	1000	$In_{0.53}Ga_{0.47}As$	p
Emitter	7000	InP	p
30 Barriers	120	$In_{0.47}Ga_{0.53}As$	i
30 Wells	120	$In_{0.62}Ga_{0.38}As$	i
Barrier	120	$In_{0.47}Ga_{0.53}As$	i
Base	5000	InP	n
Substrate		InP	n

STRAIN-BALANCED InGaAs (InP) QWC

Here we consider a 30 well strain-balanced $In_{0.62}Ga_{0.38}As/In_{0.47}Ga_{0.53}As$ (InP) QWC, whose sample description is given in Table 1. In Figure 1 the strain-balancing

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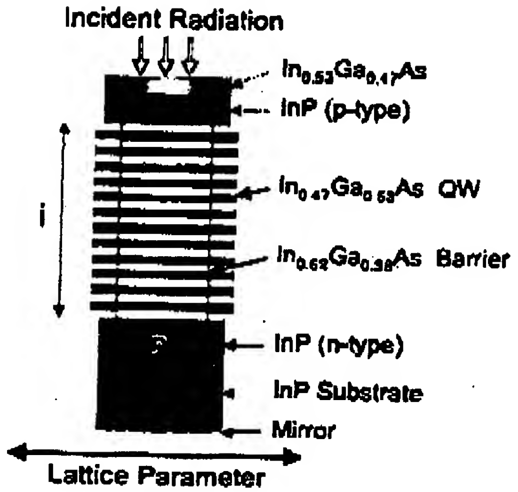

Fig. 1. Schematic drawing of a strain-balanced QWC, indicating strain-balancing conditions with regard to the lattice constants

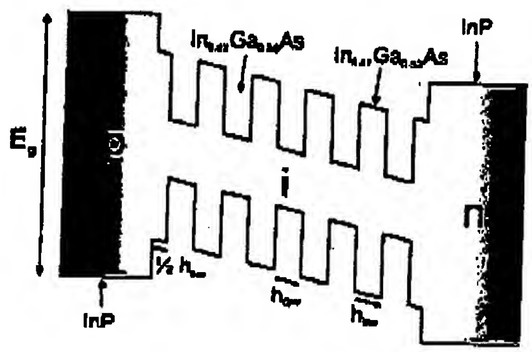

Fig. 2. Schematic drawing of the energy band-gap of a strain-balanced QWC

conditions with regard to the lattice constants are shown, and Figure 2 shows a schematic diagram of the energy band-gaps of this kind of structure.

The sample under consideration was not designed for TPV applications and the p-region, for example, is far to thick. It does not quite fulfill the ideal strain-balanced conditions, but close enough to avoid strain relaxation.

In Figure 3 we show the spectral response (SR) data of The effective band-gap, resulting from the material composition and the confinement, is about 1.77 μm, which is well beyond the band-edge of lattice-matched InGaAs The dark current density, however, is even better than in a very good lattice-matched bulk InGaAs/InP cell [7] (Figure 4). Hence the strain-balanced approach has enabled the absorption threshold to be extended out to 1.77 μm while retaining a dark current more

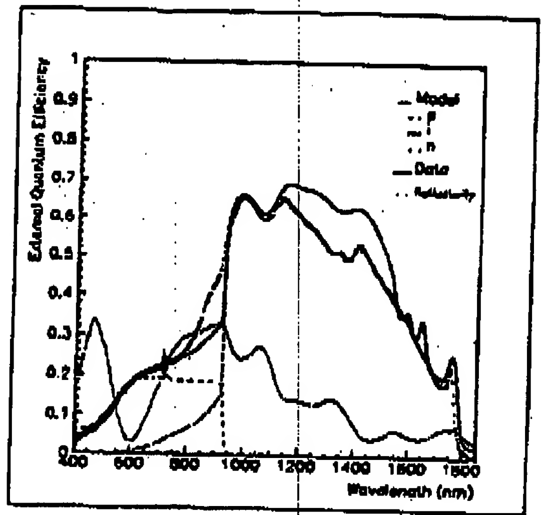

Fig. 3. SR of the strain-balanced InGaAs/InP QWC (no anti-reflection coating).

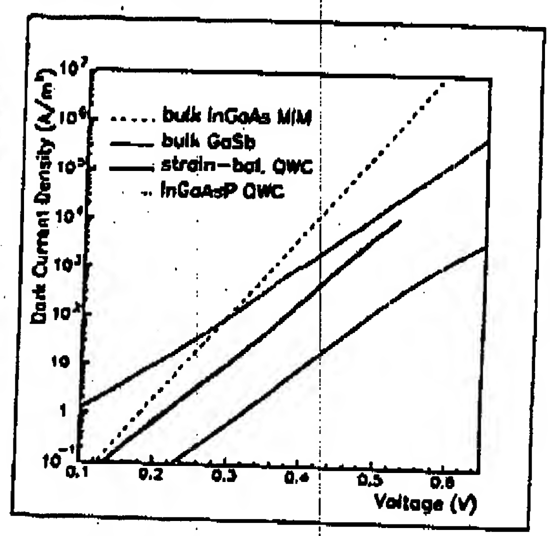

Fig 4. Dark current of a strain-balanced QWC compared with a lattice-matched QWC, bulk GaSb and InGaAs MIM.

appropriate to a cell with a band-edge of less than 1.65 μm.

We have developed a model which calculates the SR of multi-layer $In_{1-x}Ga_xAs_yP_{1-y}$ devices, lattice-matched to InP ($x \approx 0.47y$) [8,5]. It has recently been extended to estimate the SR of strain-balanced $In_{1-x}Ga_xAs/In_{1-y}Ga_yAs$ on InP [9]. The cell efficiency can be determined given the measured dark current data of the cell. In Figure 3, the SR of the strain-balanced QWC is fitted using this extended model.

Based on these results and on previously demonstrated

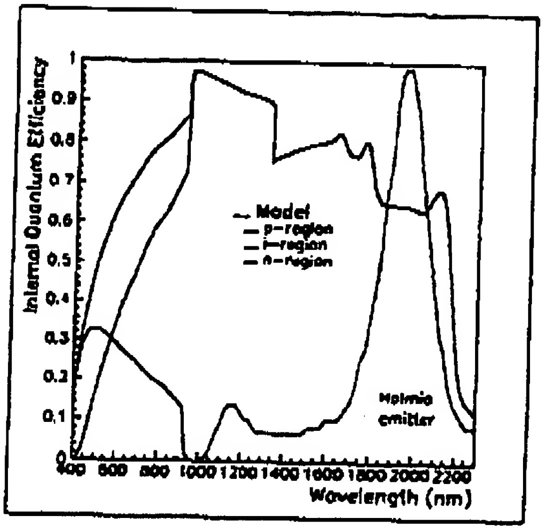

Fig. 5. Modelled internal quantum efficiency of strain-balanced QWC (with back-mirror) and Holmia spectrum (not to scale).

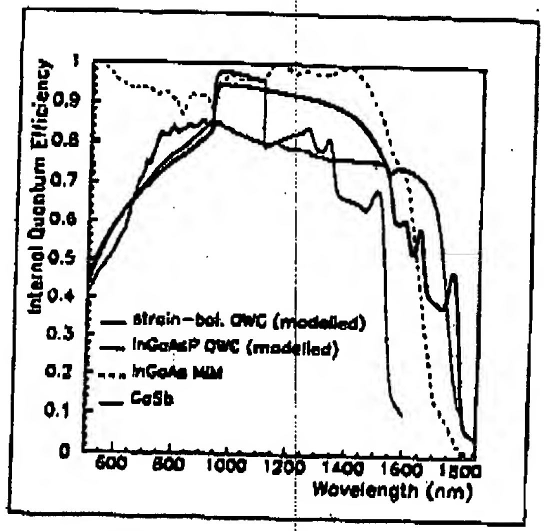

Fig. 6. Modelled internal quantum efficiency (with back-mirror) of InGaAsP QWC, bulk InGaAs MIM and GaSb. Also indicated are the spectra simulating Ytterbia and Erbia (not to scale).

modelling of lattice-matched InGaAsP [5], we model a strain-balanced QWC optimised for TPV applications with a Holmia emitter (emitting around 2 μm [13]). We therefore consider a strain-balanced QWC consisting of $In_{0.53}Ga_{0.47}As$ n- and p-regions lattice-matched to InP, and the i-region alternating 60 In[illegible]Ga[illegible]As wells with a bulk band-edge of 2.29 μm, and In[illegible]Ga[illegible]As barriers with a band-edge of 1.32 μm, both 100 Å thick, with strain-balance conditions calculated using Ref. [7]. The layers are well below the critical thickness of about 120 Å for this composition [7]. The critical thickness of strained InGaAs on InP is well described by the classical Matthews and Blakeslee force balance model [7], as has been shown experimentally by Temkin *et al.* [7] In Figures 1 and 2, schematic diagrams of this structure are shown, and Figure 5 shows the modelled spectral response.

Strain-balanced QWCs in InGaP/InGaAs on GaAs have demonstrated dark currents comparable to homogenous GaAs cells [6]. We have shown (see Figure 4) that, if anything, $In_{1-x}Ga_xAs/In_{1-y}Ga_yAs$ (InP) cells with absorption edges out to 1.77 μm have lower dark currents than bulk InGaAs cells. Hence for this projection we assume that the dark current of the modelled strain-balanced InGaAs/InP QWCs is the same as the experimental QWC result shown in Figure 4.

COMPARISON WITH BULK InGaAs MIM AND GaSb

We compare our strain-balanced QWC as well as our lattice-matched InGaAsP QWCs [9] with lattice-matched InGaAs monolithic interconnected modules (MIMs) [7], one of the best bulk InGaAs/InP TPV cells, and with bulk GaSb [11], currently the only material which is being used commercially for TPV applications [1]. The dark current of our QWCs is much lower than the homo-structure cells (Figure 4). To compare efficiencies we assume 'typical' TPV conditions of 100 kW/m² normalised power density, grid shading of 5%, and internal quantum efficiencies for all cells. A back surface reflector is an integral part of MIM technology and particularly useful for QWCs as it enhances the well contribution significantly. It also increases TPV system efficiency because longer wavelength radiation, that is not absorbed by the cell, is reflected back to the source. The effect of such a mirror is simulated by doubling the light pass through the wells.

The results for various illuminating spectra are summarised in Table 2. The relative efficiencies are rather more reliable than the absolute values.

In many cases in Table 2, the higher SR of the InGaAs MIM and GaSb (see Figure 6) is more than off-set by the lower dark current of the lattice-matched InGaAsP QWC (see Figure 4). Higher black-body temperatures, for examples 3200K and the solar spectrum AM1.5 (approximating 5800 K) at 100 times concentration, are favourable for the lattice-matched InGaAsP QWC. With narrow-band selective emitters such as Ytterbia and Erbia, which are simulated by using narrow-band filters of 950 nm and 1500 nm respectively,[3] the InGaAsP QWC has significant advantages over the InGaAs MIM and GaSb. In spectra of lower black-body temperatures (< 2000 K) the InGaAs MIM and GaSb are better than the lattice-matched InGaAsP because of the lower band-gap for bulk InGaAs and GaSb. However, at lower black-body temperature and emitters such as MgO, Erbia and Holmia, the strain-balanced QWC outperforms the others.

Table 2
Comparison of predicted efficiencies (in %) of bulk InGaAs MIM, GaSb, lattice-matched and strain-balanced QWCs with back-mirror using internal quantum efficiencies, under various spectra at 100 kW/m^2, and 5% grid shading.

Spectrum	InGaAs MIM	bulk GaSb	InGaAsP QWC	strain-bal. QWC
AM1.5G (100 suns)	16	16	20	17
3200 K blackbody	18	18	22	21
2000 K blackbody	11	11	12	13
1500 K blackbody	5.5	5.6	4.8	6.5
MgO [12]	13	15	16	22
Ytterbia-like [3]	26	25	42	31
Erbia-like [3]	37	37	46	41

CONCLUSIONS

We have demonstrated strain-balanced $In_{1-x}Ga_xAs/In_{1-y}Ga_yAs$ material in a p-i-n device on InP. We observe a dark current better than published results for a MIMs device with a band-edge of ~ 1.65 μm, even though the absorption threshold has been extended to 1.77 μm. Strain-balanced InGaAs (InP) or lattice-matched InGaAsP QWCs are predicted to have superior performance compared to state-of-the-art lattice-matched bulk InGaAs MIMs and GaSb TPV cells. Strain-balancing extends the absorption into longer wavelengths and is therefore very suitable for TPV applications particularly with a Holmia emitter

ACKNOWLEDGEMENTS

We would like to thank Navid Fatemi for information about InGaAs MIMs and Andreas Bett for information about GaSb. We are grateful to EPSRC for financial support

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Patent Application of

ROHR et al

Serial No. 09/955,297

Filed: September 19, 2001

For: PHOTOVOLTAIC DEVICE

Atty. Ref.: 550-269

Group: 1753

Examiner: Brian Mutschler

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* * * * * * * * * * *

July 17, 2003

Assistant Commissioner for Patents
Washington, DC 20231

Sir:

RULE 132 DECLARATION OF DR. NEAL G. ANDERSON

Sir:

I, Neal G. Anderson, hereby declare as follows:

(1) That I am an Associate Professor in the Department of Electrical and Computer Engineering at the University of Massachusetts at Amherst, MA., and my education and work experience are detailed in the attached *curriculum vitae* (attached as Exhibit 1).

(2) That I have read U.S. Application Serial No. 09/955,297 filed in the name of Rohr et al, the Final Rejection mailed by the Patent Office on January 27, 2003 and the below-cited prior art references referred to therein.

(3) That, with reference to the above specification, the Examiner incorrectly alleges, on page 2, section 2 of the Final Rejection, that:

(a) "The discl sure does not mention the use of such a quaternary compound;"

(b) The disclosure "does not enable one skilled in the art to use the material in the quantum well portion in the scope in which it is claimed;"

(c) "the specification does not reasonably provide enablement for GaSb or GaAs as substrates, as claimed in claims 11 and 12;" and

(d) the specification, in relations to InP substrates and InAsP or InGaAs "virtual" substrates, "does not disclose the use of the claimed material in such a way for one skilled in the are to make the claimed device."

(4) That, as an Assistant Professor (1988-1994) and Associate Professor (1994-date) I have taught undergraduate and graduate engineering students the courses listed on the last page of my attached *curriculum vitae* and am well aware of the level of skill of those persons of ordinary skill involved in the photovoltaic cell art and that such persons will have at least (a) an undergraduate degree in electrical or electronics engineering, (b) at least a masters degree in a related electrical engineering field and (c) at least 5 years experience in the photovoltaic cell field.

(5) That, in view of my experience in the field of semiconductor quantum wells and strained-layer structures from 1984 and photovoltaic cells since 1994 I can unequivocally state that the Examiner is incorrect because, with the specification teaching how to grow a multi-quantum well system according to the stress balance condition on InP substrates and InAsP or InGaAs "virtual" substrates, it would be straightforward for a person of ordinary skill in this art to apply these teachings to other Group III-V ternary or quaternary systems on GaSb and GaAs substrates.

(6) Responding directly to the Examiner's four bases of rejection:

(a) The specification describes on page 6, line 20 to page 7, line 24 how to produce a stress balanced multiple quantum well device on InP substrate and the substitution of quaternary compounds would be an obvious variant to one of ordinary skill in the art of the present disclosure;

(b) The specification explicitly describes on page 11, line 13 to page 12, line 10 the conditions to be met in producing a device according to the claimed invention in any suitable material system and thus one of ordinary skill in the art would clearly be enabled to use the material in a quantum well portion as set out in the claims thereby obtaining the benefit of the present invention;

(c) Given the explicit disclosure of the conditions to be met in any material system as described in the specification on page 11, line 12 to page 12, line 10, the specification does enable one of ordinary skill in the art to use GaSb or GaAs as substrates and obtain the benefit of the present invention; and

(d) The specific disclosure of the relationship of physical parameters to be met as set out on page 11, line 13 to page 12, line 10 is a more than sufficient disclosure so as to enable one of ordinary skill in the art to use the claimed material in making the claimed device.

(7) That, with reference to claims 10-13 & 27, the Examiner incorrectly alleges, on page 3, section 8 of the Final Rejection, that:

(a) the specification "does not reasonably provide enablement for other materials as substrates or strontium-c ntaining layers;"

(b) the specification does not enable one of ordinary skill "to make the invention commensurate in scope with these claims;"

(c) "[t]he specification does not describe the use of other materials as substrates other than InP;"

(d) "InGaAsP is the only material disclosed in depth for the quantum well and barrier layers;" and

(e) that, while the dark current behavior of an AlGaAs/GaAs QWC is shown, "no details of the cell are disclosed."

(8) That, the Examiner, in admitting that the specification is "enabling for using InP substrates and InGaAsP or AlGaAs quantum well layers and barrier layers," effectively admits enablement for the application of the invention to other materials as substrates as well as Sb containing layers.

(9) Responding directly to the Examiner's five bases of rejection, it should be understood that Sb is antimony and not strontium (this error is made throughout the official action). The specification clearly discloses a specific example device on page 6, line 20 to page 7, line 24 as well as an explicit disclosure of how the technique may be used in other suitable material systems in terms of the necessary relationship between the physical parameters thereof that should be met. As a result of the above teachings:

(a) the specification clearly does provide an enabling disclosure for other materials as substrates and antimony-containing layers;

(b) the specification clearly does enable one of ordinary skill to practice the claimed invention;

(c) the specification clearly provides an enabling disclosure for the use of materials as substrates other than InP;

(d) the specification clearly contains a sufficient disclosure such that those of ordinary skill in the art will appreciate that materials other than InGaAsP could be used for the quantum well and barrier layers; and

(e) in view of the specification, one of ordinary skill in the art could easily construct the AlGaAs/GaAs QWC cell structure that produced the dark current behavior shown in Figure 6.

(10) That, the Examiner's suggestion that every element set out in claims 1-6, 12, 13, 42 and 43 is present in the Ekins-Daukes reference ("Strain-balanced GaAsP/InGaAs quantum well solar cells" – hereinafter Ekins-Daukes I) as stated in the Final Rejection, page 5, section 12 is incorrect.

(11) Specifically, the Examiner errs in his conclusion that the requirement of claim 1 that "a period of one tensile strained layer and one compressively strained layer exerts substantially no shear force on a neighbouring structure" is ensured by the Ekins-Daukes I disclosure of a thickness-weighted average lattice constant approach as in equation 1 of Ekins-Daukes I.

(12) The Ekins-Daukes I disclosure teaches that the thickness-weighted average lattice constant of wells and barriers is roughly the same as the InP substrate but this is insufficiently exact to ensure periods which exert "substantially no shear force on a neighboring structure."

(13) I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and

further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Enclosure: Exhibit 1

7.17.03
Date

Dr. Neal G. Anderson

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Serial No. 09/955,297

Exhibit 1 – CV for

Neal G. Anderson

Department of Electrical and Computer Engineering
University of Massachusetts at Amherst
Amherst, MA 01003-5110

CURRENT

Associate Professor – Recent research activities in quantum semiconductor heterostructures and their applications in solar cells, lasers, and blue/UV optoelectronics. Current interests include physical information theory and its engineering implications and applications.

EDUCATION

Ph.D. in Electrical Engineering - August, 1988.
North Carolina State University, Raleigh, North Carolina.
Dissertation: "Strained-Layer InGaAs-GaAs Heterojunctions, Quantum Wells and Superlattices: Electronic Structure and Optical Properties" (Chair: Robert Kolbas).

PROFESSIONAL ASSOCIATIONS

- IEEE
- APS
- Optical Society of America
- Philosophy of Science Association
- AAAS

SELECTED RECENT PUBLICATIONS, PRESENTATIONS AND REPORTS

Neal G. Anderson
"Quantum Channels with Limited Access"
Invited talk presented at the Special Session on Quantum Information Theory: 979th Meeting of the American Mathematical Society, Boston, October 2002. Manuscript in preparation.

Neal G. Anderson
"On Quantum Well Solar Cell Efficiencies"
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"An Optically Pumped GaN-AlGaN Vertical Cavity Surface Emitting Laser"

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TEACHING ACTIVITIES

Undergraduate Courses

ENGIN 112 Introduction to Electrical and Computer Engineering
ECE 303 Junior Seminar
ECE 316 Semiconductor Materials and Devices (now ECE 344)
ECE 494 Professional Seminar
ECE 571 Microelectronic Fabrication
ECE 572 Optoelectronics

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ECE 609 Semiconductor Devices
ECE 618 Fundamentals of Solid State Electronics II
ECE 697 Quantum Information Theory
ECE 722 Physical Semiconductor Electronics
ECE 723 Quantum Electronics (formally "Introduction to Masers and Lasers")

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